On the Resource Allocation for D2D Underlaying Uplink Cellular Networks

Adeola Omorinoye, Quoc-Tuan Vien, Tuan Anh Le, Purav Shah
Faculty of Science and Technology
Middlesex University
London, UK
AO991@live.mdx.ac.uk;{Q.Vien;T.Le;P.Shah}@mdx.ac.uk

***Abstract*—Deice-to-Device (D2D) communications has attracted research interests as an emerging technology towards 5G and beyond cellular networks. In this paper, we investigate the power allocation in D2D underlaying cellular networks with uplink channel reuse. We first develop an optimization problem to minimize the total power consumption subject to per-user Quality-of-Service (QoS) constraints. A distributed power allocation algorithm is proposed to allocate the power for both D2D and cellular users by exploiting the property of strictly non-negative inverse of a Z-matrix. It is shown that the power allocated for users can be considerably saved for low QoS requirements, especially with a large number of D2D users. The proposed algorithm is validated through simulation to realize the impacts of noise power, distance between D2D users and the number of D2D pairs in the network.**

***Index Terms*—Device-to-device communication, uplink, power allocation.**

I. Introduction

The rise in the number of cellular users (CUs) has led to an exponential increase in mobile traffic in the last few decades. A number of efforts have been devoted to handling such increasing number of CUs. Although the base stations (BSs) along with the development of small cells in the current cellular systems can cover a large area providing an enhanced Quality-of-Service (QoS), they may require increased capital expenditure and operating expenses. The limited spectrum resources and the availability of licensed spectrum also restrain the network scalability. Dealing with these issues, device-to-device (D2D) communications is promising to have a wide variety of applications in next generation wireless networks. The D2D was proposed as a novel technology that allows the users to communicate directly with each other without going through the BSs by sharing the cellular frequency bands, and hence named as D2D underlaying cellular networks [1].

The D2D is being considered as one of the key enabling technologies in 5G cellular networks because of its constitutional need for enhanced QoS with high data rate and low latency [1], [2]. In D2D underlaying cellular networks, the licensed spectrum of the CUs can be reused by the D2D users, while still maintaining the QoS of the CUs [3]. The D2D has been applied in many areas including proximity based services [4], cellular offloading [5], public safety services [6], multi hop relaying [7], and vehicular networks [8]. Resource allocation is however one of the major concerns in the D2D underlaying cellular network [9].

Recently, many works have been carried out to optimize resource allocation for D2D communications in an interference limited environment [10], [11], [12]. Practically, the D2D users and CUs are handheld devices which rely on battery, and thus suffer from battery drain problem if the power allocation is not properly designed. In this paper, we investigate the resource allocation in D2D underlaying cellular networks where the D2D users exploit the uplink channels of the CUs.

We first develop an optimization problem to find the optimal power for D2D users and CUs so as to minimize the total power consumption of the system subject to per-user QoS constraints in terms of the required signal-to-interference-plus-noise ratio (SINR) and limited transmit power at each user. In order to solve the developed problem, a power allocation mechanism is then proposed by exploiting the property of Z-matrix. The impacts of noise power, distance between D2D users and the number of D2D users are investigated and validated through the simulation. The results show that the proposed algorithm can accommodate all the D2D users without affecting the CU allowing all devices to share the limited resources at the same time. In particular, the proposed algorithm is shown to save the transmit power of the D2D users with low QoS requirements, which accordingly results in an increase in the overall system's energy efficiency.

II. System Model

Figure 1 illustrates the system model of a D2D underlaying cellular network under investigation. An uplink scenario is considered in a network consisting of a BS, a CU and N pairs of D2D users. Operating together with the cellular network, N D2D transmitters $\{DT_1, DT_2, \ldots, DT_N\}$ send their data to N desired D2D receivers $\{DR_1, DR_2, \ldots, DR_N\}$ using the same uplink frequency band which is allocated for the link from the CU to the BS. Therefore, the D2D receivers suffer from the interference of not only other D2D transmitters, but also the CU. Meanwhile, the BS also receives the undesired signals from the D2D transmitters in addition to those from the CU.

Let $d_{b,c}$, $d_{i,j}$, $d_{j,c}$, and $d_{b,i}$, $\{i, j\} \in \{1, 2, \ldots, N\}$, denote the distances between CU and BS, between DR_i and DT_j,

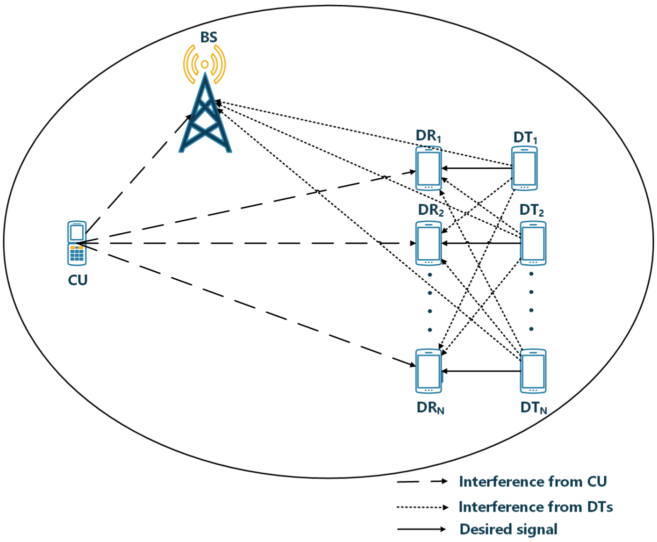

Fig. 1. System Model

between CU and DR_j, and between DT_i and BS, respectively. The links CU $\to$ BS, $DT_j \to DR_i$, CU $\to DR_j$, and $DT_i \to$ BS, $\{i, j\} \in \{1, 2, \ldots, N\}$, are assumed to experience Rayleigh flat fading channels having channel coefficients $h_{b,c}$, $h_{i,j}$, $h_{j,c}$, and $h_{b,i}$, respectively, with $E[|h_{b,c}|^2] = 1/d_{b,c}^{\alpha}$, $E[|h_{i,j}|^2] = 1/d_{i,j}^{\alpha}$, $E[|h_{j,c}|^2] = 1/d_{j,c}^{\alpha}$, and $E[|h_{b,i}|^2] = 1/d_{b,i}^{\alpha}$. Here, $E[\cdot]$ denotes the expectation operator and α is the pathloss exponent depending on the propagation environment.

Over uplink channel, the received signal at BS is given by

$$y_b = \sqrt{p_c} h_{b,c} x_c + \sum_{i=1}^{N} \sqrt{p_i} h_{b,i} x_i + n_b, \tag{1}$$

where x_c and x_i, $i = 1, 2, \ldots, N$, are signals transmitted from CU and DT_i with transmit power p_c and p_i, respectively, and n_b is an independent circularly symmetric complex Gaussian (CSCG) noise having zero mean and variance of $E[|n_b|^2] = N_0$.

The instantaneous SINR at the BS of the cellular communications is thus given by

$$\gamma_b = \frac{p_c |h_{b,c}|^2}{\sum_{i=1}^{N} p_i |h_{b,i}|^2 + N_0}. \tag{2}$$

Considering the D2D communications, the received signal at D2D receiver DR_i, $i = 1, 2, \ldots, N$, can be written as

$$y_i = \sum_{j=1}^{N} \sqrt{p_j} h_{i,j} x_j + \sqrt{p_c} h_{i,c} x_c + n_i, \tag{3}$$

where x_j, $j = 1, 2, \ldots, N$, are signals transmitted from DT_j with transmit power p_j and n_i is an independent CSCG noise having zero mean and variance of $E[|n_i|^2] = N_0$.

Note that DR_i, $i = 1, 2, \ldots, N$, is only interested in x_i from DT_i. The instantaneous SINR at DR_i of the D2D communications is thus given by

$$\gamma_i = \frac{p_i |h_{i,i}|^2}{\sum_{j=1, j \neq i}^{N} p_j |h_{i,j}|^2 + p_c |h_{i,c}|^2 + N_0}. \tag{4}$$

For simplicity, let us denote the channel gains of the links CU $\to$ BS, $DT_j \to DR_i$, CU $\to DR_j$, and $DT_i \to$ BS, $\{i, j\} \in \{1, 2, \ldots, N\}$, as $g_{b,c} = |h_{b,c}|^2$, $g_{i,j} = |h_{i,j}|^2$, $g_{j,c} = |h_{j,c}|^2$, and $g_{b,i} = |h_{b,i}|^2$, respectively. The instantaneous SINR and BS and DR_i, $i = 1, 2, \ldots, N$, in (2) and (4) can be respectively rewritten as

$$\gamma_b = \frac{p_c g_{b,c}}{\sum_{i=1}^{N} p_i g_{b,i} + N_0}, \tag{5}$$

$$\gamma_i = \frac{p_i g_{i,i}}{\sum_{j=1, j \neq i}^{N} p_j g_{i,j} + p_c g_{i,c} + N_0}. \tag{6}$$

III. Proposed Optimization problem for both D2D and Cellular Communications

In this paper, we aim to minimise the transmission power of all the users in the network, i.e, all D2D and cellular users, subject to maintaining the required SINR for all users and their limited transmit power. To that end, we propose the following optimization problems. First, we introduce the optimization problem for the D2D communications as follows:

$$\begin{aligned} \min_{p_i} \quad & \sum_{i=1}^{N} p_i, \\ \text{s. t.} \quad & \gamma_i \geqslant \bar{\gamma}_i, \forall i = 1, \ldots, N, \\ & p_i \leq p_i^{\max}, \forall i = 1, \ldots, N, \end{aligned} \tag{7}$$

where γ_i is given by (6), $p_i^{\max}$ is the maximum transmit power at DT_i, $\bar{\gamma}_i$ is the required SINR level at DR_i.

Next we consider cellular uplink communications with the following optimization problem:

$$\begin{aligned} \min_{p_c} \quad & p_c, \\ \text{s. t.} \quad & \gamma_b \geqslant \bar{\gamma}_b, \\ & p_c \leq p_c^{\max}, \end{aligned} \tag{8}$$

where γ_b is given by (5), $p_c^{\max}$ is the maximum transmit power at the CU, and $\bar{\gamma}_b$ is the required SINR level at the BS.

For the sake of convenience, we combine problems (7) and (8) in the following form:

$$\begin{aligned} \min_{p_i} \quad & \sum_{i=1}^{N+1} p_i, \\ \text{s. t.} \quad & \frac{p_i g_{i,i}}{\sum_{j=1, j \neq i}^{N+1} p_j g_{i,j} + N_0} \geqslant \bar{\gamma}_i, \forall i = 1, \ldots, N+1, \\ & p_i \leq p_i^{\max}, \forall i = 1, \ldots, N+1, \end{aligned} \tag{9}$$

where we have slightly abused the notation by using the index $N+1$ to represent either c for D2D communications or b for cellular communications, i.e. $p_{N+1} = p_c$, $g_{i,N+1} = g_{i,c}$, $g_{N+1,j} = g_{b,j}$, $g_{N+1,N+1} = g_{b,c}$, and $\bar{\gamma}_{N+1} = \bar{\gamma}_b$.

Rearranging the SINR constraints in (9), one can rewrite the optimization problem (9) in the following equivalent form:

$$\min_{p_i} \quad \sum_{i=1}^{N+1} p_i,$$

$$\text{s. t.} \quad p_i g_{i,i} - \bar{\gamma}_i \sum_{j=1, j\neq i}^{N+1} p_j g_{i,j} \geqslant N_0 \bar{\gamma}_i, \forall i = 1, 2, \ldots, N+1,$$
$$p_i \leq p_i^{\max}, \forall i = 1, 2, \ldots, N+1,, \tag{10}$$

We continue by introducing $\mathbf{G}$, $\mathbf{p}$, and $\mathbf{n}$ as follows.

$$\mathbf{G} \triangleq \begin{bmatrix} g_{1,1} & -\bar{\gamma}_1 g_{1,2} & \cdots & -\bar{\gamma}_1 g_{1,N} & -\bar{\gamma}_1 g_{1,c} \\ -\bar{\gamma}_2 g_{2,1} & g_{2,2} & \cdots & -\bar{\gamma}_2 g_{2,N} & -\bar{\gamma}_2 g_{2,c} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ -\bar{\gamma}_N g_{N,1} & -\bar{\gamma}_N g_{N,2} & \cdots & g_{N,N} & -\bar{\gamma}_N g_{N,c} \\ -\bar{\gamma}_b g_{b,1} & -\bar{\gamma}_b g_{b,2} & \cdots & -\bar{\gamma}_b g_{b,N} & g_{b,c} \end{bmatrix}, \tag{11}$$

$$\mathbf{p} \triangleq \begin{bmatrix} p_1 & p_2 & \cdots & p_N & p_c \end{bmatrix}^T, \tag{12}$$

$$\mathbf{n} \triangleq \begin{bmatrix} N_0\bar{\gamma}_1 & N_0\bar{\gamma}_2 & \cdots & N_0\bar{\gamma}_N & N_0\bar{\gamma}_b \end{bmatrix}^T, \tag{13}$$

$$\mathbf{p}_{\max} \triangleq \begin{bmatrix} p_1^{\max} & p_2^{\max} & \cdots & p_N^{\max} & p_c^{\max} \end{bmatrix}^T. \tag{14}$$

Hence, the problem (10) can be equivalently restated as

$$\begin{aligned} \min_{p_i} \quad & \sum_{i=1}^{N+1} p_i, \\ \text{s. t.} \quad & \mathbf{G}\mathbf{p} \succeq \mathbf{n}, \\ & \mathbf{p} \preceq \mathbf{p}_{\max}. \end{aligned} \tag{15}$$

where $\succeq$ and $\preceq$ are used to denote the element-wise-inequality operators.

In order to find the optimal solution to problem (15), we introduce the following lemma.

Lemma 1. *If matrix* $\mathbf{G}$ *defined in* (11) *satisfies*

$$g_{i,i} > \bar{\gamma}_i \sum_{j=1, j\neq i}^{N+1} g_{i,j}, \forall i = 1, 2, \ldots, N+1, \tag{16}$$

then there exists a unique lower bound for the power allocation for problem (15) *as*

$$\mathbf{p}_{min} = \mathbf{G}^{-1}\mathbf{n}. \tag{17}$$

Proof. The proof is similar to that in [13], [14], [15]. Here, it is sketched as follows. By observing (11), one can conclude that all the off-diagonal elements of matrix $\mathbf{G}$ are non-positive. Hence, according to [16], [17], matrix $\mathbf{G}$ is called a *Z-matrix*. If $\mathbf{G}$ satisfies the condition in (16), then $\mathbf{G}$ is strictly diagonally dominant matrix. According to [13, chapter 6, Theorem 2.3], all principal minors of $\mathbf{G}$ are positive. Since $\mathbf{G}$ is a *Z-matrix*, according to [14, theorem 3.11.10], $\mathbf{G}^{-1}$ exist and all its elements are non-negative. Since all the elements of vector $\mathbf{n}$ in (13) are also non-negative, then $\mathbf{p}$ is lower bounded by $\mathbf{p}_{\min} = \mathbf{G}^{-1}\mathbf{n} \succeq 0$. This concludes the proof. □

Remark 1. *If* $\mathbf{p}_{min}$ *defined in* (17) *also satisfies*

$$\mathbf{p}_{min} \preceq \mathbf{p}_{max}, \tag{18}$$

then $\mathbf{p}_{min}$ *is the optimal solution to the proposed problem* (15).

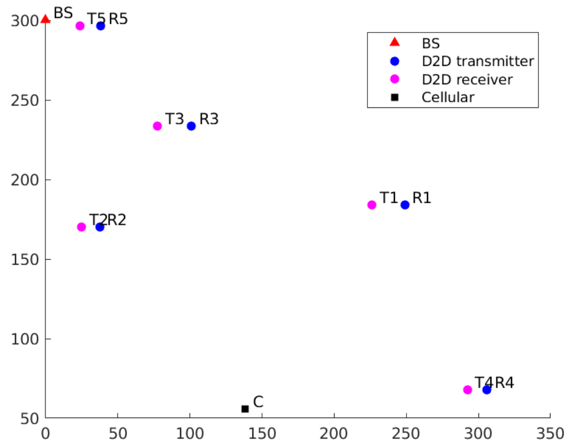

Fig. 2. A typical example of simulation model for a D2D underlaying cellular network consisting of a BS, a CU, and 5 pairs of D2D users within an area of 300 m × 300 m.

IV. Simulation Results

This section provides the simulation results of the proposed power allocation in a D2D underlaying cellular network. In the simulation, the nodes are located within an area of 300 m × 300 m, the pathloss exponent is set as $\alpha = 2$, the required SINR of all D2D users and CU are equally set and varies as $\bar{\gamma}_i = \bar{\gamma}_b \in [-20, 20]$ dB, $\forall i = 1, 2, \ldots, N$, and the maximum transmit power is $p_i^{\max} = p_c^{\max} = 30$ dBm. It is assumed that BS is at the top left corner, i.e. $\{x_{BS}, y_{BS}\} = \{300, 300\}$ m, while the location of other nodes, i.e. CU and D2D users, is uniformly distributed in the range $[0, 300]$ m. Due to the requirement that mobile devices should be in short range for D2D communications, the distance between the D2D transmitter and D2D receiver of a pair is limited in $[d_{\min}, d_{\max}]$, where 10 m $\leqslant d_{\min} < d_{\max} \leqslant$ 50 m. An illustration of the simulation settings is shown in Fig. 2 where 5 pairs of D2D users are plotted with $d_{\min} = 10$ m and $d_{\max} = 25$ m.

Considering the impact of noise power on the power allocation, Fig. 3 plots the average transmit power of D2D transmitters, i.e. $E[\mathbf{p}_{\min}]$, versus required SINR, i.e. $\bar{\gamma}$, with respect to three values of noise power $N_0 \in \{-30, -40, -50\}$ dBm. Five pairs of D2D users, i.e. $N = 5$, are considered and the distance between each D2D pair is uniformly distributed in the range $[10, 25]$ m. It can be seen in Fig. 3 that the required transmit power increases as the SINR requirement increases. Also, a higher transmit power is required to compensate an increased noise power. For instance, when the SINR is 5 dB, the average transmit power required is 10 dBm with noise power of -30 dBm compared to when the noise power of -50 dBm with an average transmit power of 0 dBm. In Fig. 3, the graph is fluctuating due to the fact that the instantaneous SINR is considered over different fading generations, among which some cause the matrix $\mathbf{G}$ defined in (11) is not invertible, i.e. does not satisfy the condition in Lemma 1.

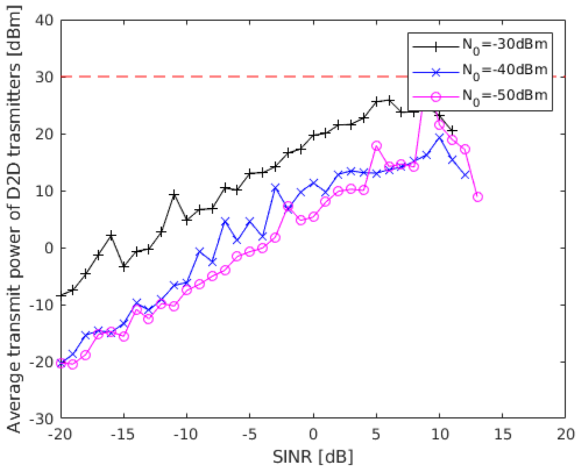

Fig. 3. The average transmit power of D2D transmitters versus required SINR with respect to different noise power.

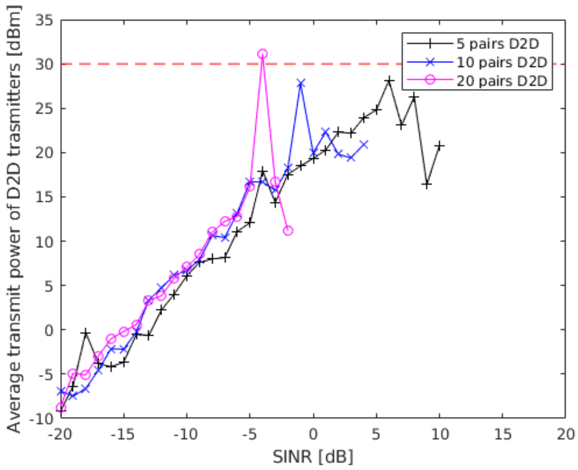

Fig. 5. The average transmit power of D2D transmitters versus required SINR with respect to the number of D2D users.

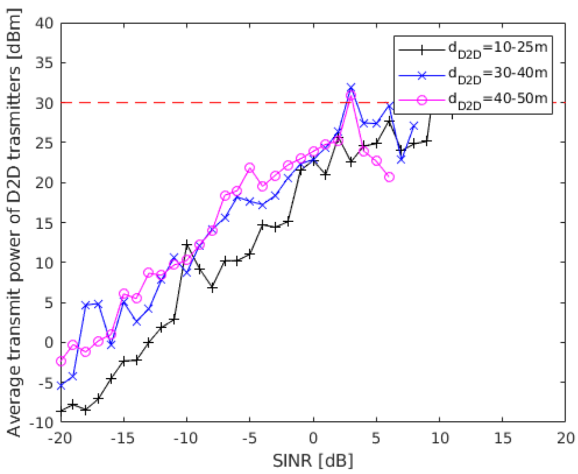

Fig. 4. The average transmit power of D2D transmitters versus required SINR with respect to distance between D2D users.

The impacts of the distance between D2D users are validated in Fig. 4 where the average transmit power of D2D transmitters is plotted over the required SINR with respect to three cases of distance between D2D users, i.e. $\{[d_{\min}, d_{\max}]\} \in \{[10,25],[30,40],[40,50]\}$ m. The noise power is fixed as $N_0 = -30$ dBm. There are five pairs of D2D users and their locations are similarly set as in Fig. 3. It can be observed that the D2D users having distance within 40 m to 50 m require a higher transmit power compared to those with shorter distance. As an example in Fig. 4, when the SINR requirement is -5 dB, the average transmit power required for the D2D users with a distance of 10 - 20 m, 30 - 40 m and 40 - 50 m are 10 dBm, 15 dBm, and 20 dBm, respectively. This means that, in order to satisfy the SINR requirement, the distance between the D2D users has a considerable impact on the average transmit power at the D2D users.

Taking into account the number of D2D users, Fig. 5 plots the average transmit power of D2D transmitters against the required SINR for three cases of the number of D2D pairs, i.e. $N \in \{5, 10, 20\}$. In this figure, the noise power is similarly set as in Fig. 4, i.e. $N_0 = -30$ dBm, while the distance between D2D users is varied as in Fig. 3 in the range $[10, 25]$ m. It can be observed that there is not much difference in the average transmit power required at the D2D users regardless of the number of D2D pairs. This accordingly verifies that our proposed algorithm can be applied for any number of D2D pairs.

V. Conclusion

In this paper, we have developed an optimization problem to find the optimal power allocation for D2D users and CU in D2D underlaying cellular networks subject to QoS constraints in terms of SINR requirement at each user and their limited power constraint. An optimal power allocation has been proposed by exploiting the property of strictly non-negative inverse of a Z-matrix. The proposed approach has been shown to be able to provide an optimal solution when the generation matrix satisfies the condition for a Z-matrix. Moreover, the impacts of noise power, the distance between D2D users and the number of D2D pairs have been discussed and validated through the simulation. It has been shown that either a higher noise power or a farther distance of the D2D users requires an increased transmit power of the D2D users, whereas deploying more number of D2D pairs does not have much impact on the required transmit power of the D2D users.

References

[1] D. Feng, L. Lu, Y. Yuan-Wu, G. Y. Li, G. Feng, and S. Li, "Device-to-device communications underlaying cellular networks," *IEEE Transactions on Communications*, vol. 61, no. 8, pp. 3541–3551, August 2013.

[2] E. Hossain and M. Hasan, "5g cellular: key enabling technologies and research challenges," *IEEE Instrumentation Measurement Magazine*, vol. 18, no. 3, pp. 11–21, June 2015.

[3] H. Q. Tran, C. V. Phan, and Q.-T. Vien, *"An overview of 5G technologies. In: Emerging Wireless Communication Network Technologies: Principle, Paradigm and Performance"*. Springer, 2018.

[4] H. A. S. Doumiati and D. M. Gutierrez-Estevez, "A framework for lte-a proximity-based device-to-device service registration and discovery," *Procedia Computer Science*, vol. 34, pp. 87–94, 2014.

[5] L. Al-Kanj, H. V. Poor, and Z. Dawy, "Optimal cellular offloading via device-to-device communication networks with fairness constraints," *IEEE Transactions on Wireless Communications*, vol. 13, no. 8, pp. 4628–4643, Aug 2014.

[6] M. Usman, A. A. Gebremariam, U. Raza, and F. Granelli, "A software-defined device-to-device communication architecture for public safety applications in 5g networks," *IEEE Access*, vol. 3, pp. 1649–1654, 2015.

[7] S. Wen, X. Zhu, Y. Lin, Z. Lin, X. Zhang, and D. Yang, "Achievable transmission capacity of relay-assisted device-to-device (d2d) communication underlay cellular networks," in *2013 IEEE 78th Vehicular Technology Conference (VTC Fall)*, Sep. 2013, pp. 1–5.

[8] G. Piro, A. Orsino, C. Campolo, G. Araniti, G. Boggia, and A. Molinaro, "D2d in lte vehicular networking: System model and upper bound performance," in *2015 7th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*, Oct 2015, pp. 281–286.

[9] K. Ali, H. X. Nguyen, Q. T. Vien, P. Shah, and Z. Chu., "Disaster management using d2d communication with power transfer and clustering techniques," *IEEE Access*, vol. PP, no. 99, pp. 1–1, 2018.

[10] C. Yu, K. Doppler, C. B. Ribeiro, and O. Tirkkonen, "Resource sharing optimization for device-to-device communication underlaying cellular networks," *IEEE Transactions on Wireless Communications*, vol. 10, no. 8, pp. 2752–2763, August 2011.

[11] C. Xu, L. Song, Z. Han, Q. Zhao, X. Wang, X. Cheng, and B. Jiao, "Efficiency resource allocation for device-to-device underlay communication systems: A reverse iterative combinatorial auction based approach," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 9, pp. 348–358, Sep. 2013.

[12] F. Wang, L. Song, Z. Han, Q. Zhao, and X. Wang, "Joint scheduling and resource allocation for device-to-device underlay communication," in *2013 IEEE Wireless Communications and Networking Conference (WCNC)*, April 2013, pp. 134–139.

[13] A. Attar, M. R. Nakhai, and A. H. Aghvami, "Cognitive radio game for secondary spectrum access problem," *IEEE Transactions on Wireless Communications*, vol. 8, no. 4, pp. 2121–2131, April 2009.

[14] T. A. Le and M. R. Nakhai, "Downlink optimization with interference pricing and statistical csi," *IEEE Transactions on Communications*, vol. 61, no. 6, pp. 2339–2349, June 2013.

[15] T. A. Le and K. Navaie, "Downlink beamforming in underlay cognitive cellular networks," *IEEE Transactions on Communications*, vol. 62, no. 7, pp. 2212–2223, July 2014.

[16] A. Berman and R. Plemmons, *"Nonnegative Matrices in the Mathematical Sciences"*. Society for Industrial and Applied Mathematics, 1994. [Online]. Available: https://epubs.siam.org/doi/abs/10.1137/1.9781611971262

[17] R. Cottle, J. Pang, and R. Stone, *"The Linear Complementarity Problem"*. Society for Industrial and Applied Mathematics, 2009. [Online]. Available: https://epubs.siam.org/doi/abs/10.1137/1.9780898719000